ROLE OF HELICON MODES IN SUBSTORM PROCESSES

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Abstract. It is shown that the presence of an ionospheric-origin anisotropic oxygen ion beam can excite a helicon mode instability in the near-Earth plasma sheet region. For the case of a nonneutral ionospheric oxygen ion beam passing through the plasma sheet region (corresponding to a finite field-aligned current in the equilibrium state), the helicon modes are found to be excited below (or comparable to) the oxygen ion cyclotron frequencies. On the other hand, for the case of a neutralized (i.e., carrying no net field-aligned current) weakly magnetized oxygen ion beam , both the helicon modes and the LH modes are excited. An interesting feature of the helicon mode instability is that it could be excited under the conditions when the usual long wavelength fire-hose modes are stable. The typical e-folding time of the instability is about a few minutes. Therefore these modes are likely to attain saturation during enhanced convection events and could significantly affect substorm dynamics. Large amplitude helicon modes could twist the ambient magnetic field and may be observable as flux ropes. Low-frequency turbulence produced by these modes could scatter electrons trapped in the inner central plasma sheet region and help excite the ion tearing modes, leading to substorm onset.

1. Introduction

Recent observations suggest that ionospheric-origin O^+ ions consititute an important and sometimes dominant part of the outer magnetosphere and the near-Earth plasmasheet region [*Peterson et al.*, 1981; *Sharp et al.*, 1981; *Lennartsson*, 1994; *Shelley et al.*, 1982; *Hultqvist*, 1991; *Lennartsson and Shelley*, 1986; *Daglis et al.*, 1991, 1993, 1994]. Observations by GEOTAIL indicate the presence of tailward flowing energetic O^+ ion bursts in the distant magnetotail [*Wilken et al.*, 1995]. Two most important ionospheric outflow regions for the O^+ ions are the auroral region and the dayside cleft [*Lockwood et al.*, 1985; *Delcourt et al.*, 1989; *Cladis and Francis*, 1992]. *Daglis and Axford* [1996] have shown that auroral ionospheric ion feeding of the inner plasmasheet during substorms can be fast (i.e.. $\sim$ characteristic substorm timescales). Therefore, the ionosphere could actively influence the substorm energization processes by strongly responding to the solar wind.

It is interesting to note that ionospheric O^+ ion fluxes in the near-Earth plasmasheet ($X \sim$ -$6R_E$ to -15 R_E) are observed to increase dramatically during the growth phase of substorms [*Daglis et al.*, 1991; *Kistler et al.*, 1992]. Thus, the O^+ ions would exert pressure in the region of the plasmasheet where the near-Earth neutral line is expected to form. The presence of ionospheric O^+ ions would influence the dynamical evolution of the plasmasheet. For example, enhanced densities of ionospheric O^+ ions in some localized region in the plasmasheet could excite several plasma instabilities, such as, ion tearing instability [*Schindler*, 1974; *Baker et al.*, 1982], velocity shear instabilities [*Cladis and Francis*, 1992], firehose type instabilities [*Davidson and Völk*, 1968; *Verheest and Lakhina*, 1991; *Hill and Voigt*, 1992; *Yoon et al.*, 1993; *Lakhina*, 1995, 1996], which could lead to the onset of the substorms. Thus, it is important to study the effects of ionospheric O^+ ions on the stability and dynamics of the near-Earth plasmasheet which ultimately controls the substorm processes.

In an electron-proton plasma, the dispersion relation for the right-hand polarized low-frequency modes, i.e., $\omega \ll \Omega_p$ (here ω and Ω_p represent the wave and the proton cyclotron frequencies, respectively), propagating parallel to the magnetic field, $\mathbf{B}_0$, gives the MHD Alfvén modes. In this case the proton Hall current completely cancels the electron Hall current, and the wave is maintained by the proton polarization current [*Papadopoulos et al*, 1994]. However, in the presence of oxygen ions, the ion (both proton and oxygen) Hall currents cannot completely cancel the electron Hall current unless $\omega \ll \Omega_o$ (Ω_o being the oxygen ion cyclotron frequency). Therefore for the case when O^+ ions are weakly magnetized or unmagnetized, they carry negligible Hall current, and the resultant ion Hall current is not sufficient to neutralize the electron Hall current. This situation could give rise to helicon waves [*Papadopoulos et al.*, 1994; *Zhou et al.*, 1996; *Lakhina and Tsurutani*, 1997]. The helicon waves could lead to the fast current and flux penetration across the plasma sheet [*Papadopoulos et al.*, 1994], thus affecting the sub-

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storm dynamics. Here, we show the possibility of driving the helicon mode instability in the magnetotail by the ionospheric-origin oxygen ion beams.

2. Helicon Mode Instability

The dispersion relation for the electromagnetic modes propagating parallel to the magnetic field, $\mathbf{B_0} = B_0\mathbf{x}$ in a multispecies plasma can be written [*Lakhina*, 1995; *Lakhina and Tsurutani*, 1997], in standard notation,

$$\begin{aligned}\omega^2 &= c^2k^2 - \sum_j \omega_{pj}^2 \left[\frac{\omega - kU_j}{k\alpha_{\parallel j}} Z(\eta_j) \right. \\ &\quad \left. + \left(\frac{\alpha_{\perp j}^2}{\alpha_{\parallel j}^2} - 1\right)\{1 + \eta_j Z(\eta_j)\}\right], \qquad (1)\end{aligned}$$

where $\omega_{pj} = (4\pi q^2 N_j/m_j)^{1/2}$ and $\Omega_j = q_j B_0/m_j c$ are the plasma and the gyrofrequency of the jth species, with $j = e, p$ and o for electrons, protons and the oxygen ions respectively, U_j is the drift velocity of the jth species, and $\alpha_{\perp j}$ and $\alpha_{\parallel j}$ are respectively the perpendicular and parallel thermal velocities with respect to $\mathbf{B_0}$, and $Z(\eta_j)$ is the well known plasma dispersion function with the argument $\eta_j = (\omega - kU_j \pm \Omega_j)/k\alpha_{\parallel j}$. The $\pm$ sign in η_j denotes the RH (+ sign) and the LH (− sign) modes. In writing (1), we have taken the distribution functions as drifted bi-Maxwellians. In the equilibrium state, the charge neutrality is maintained by taking $N_e = N_p + N_o$, where N is density.

For the case of $\eta_j \gg 1$ for each species, (1) can be simplified to,

$$\begin{aligned}\omega^2 &= c^2k^2 + \sum_j \omega_{pj}^2 \left[\frac{\omega - kU_j}{\omega - kU_j \pm \Omega_j} \right. \\ &\quad \left. + \frac{(\alpha_{\perp j}^2 - \alpha_{\parallel j}^2)k^2}{2(\omega - kU_j \pm \Omega_j)^2}\right], \qquad (2)\end{aligned}$$

We shall solve (2) in the proton rest frame, i.e., $U_p = 0$, and will consider two special cases, namely, 1) a nonneutral ionospheric oxygen ion beam passing through the plasmasheet region (corresponding to a finite field-aligned current in the equilibrium state), and 2) a neutralized oxygen ion beam (i.e., the current neutrality is maintained in the equilibrium state).

2.1 Nonneutral O^+ ion beam

The case of ionospheric O^+ ion beam passing through the stationary ($U_p = 0$, and $U_e = 0$) plasmasheet region corresponds to the situation of a finite field-aligned current in the system. Then, for $(\omega - kU_j)^2 \ll \Omega_j^2$ for $j = e$ (electrons) and p (protons), and $\omega^2 \ll c^2$, (2) can be written as

$$\omega^2 \pm \frac{N_o m_e}{N_p m_p}\Omega_e\omega - k^2V_{Ap}^2\left(1 - \frac{A_e}{2} - \frac{A_p}{2}\right)$$

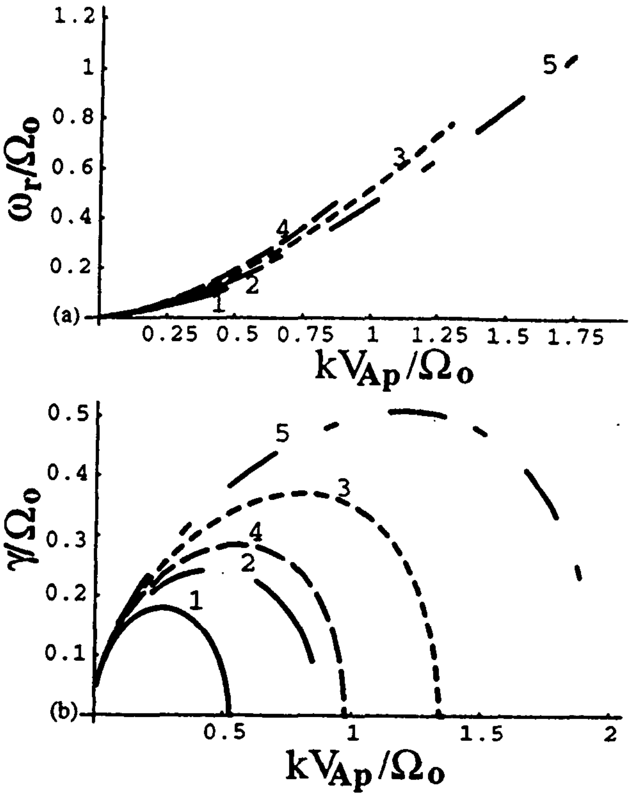

Figure 1. Variation of normalized real frequency ω_r/Ω_o (a), and growth rate γ/Ω_o (b) versus normalized wavenumber kV_{Ap}/Ω_o for the helicon mode instability driven by O^+ ions in the CPS region for $M = U_o/V_{Ap} = 0.25$, $R = \rho_o/\rho_p = 1.0$, $A_e = A_p = 0$, and $\beta_{\parallel o} = 3.5$. The curves 1, 2, 3, and 4 are respectively for $A_o = (\beta_{\parallel o} - \beta_{\perp o}) = 0.1, 0.5, 1.0$, and 2.0. For the parameters considered here as well as in Figures 2, the LH mode instability does not exist.

$$-\frac{N_o}{N_p}\frac{\Omega_p\Omega_o(\omega - kU_o)}{\omega - kU_o \pm \Omega_o} + \frac{A_o k^2 V_{Ap}^2 \Omega_o^2}{2(\omega - kU_o \pm \Omega_o)^2} = 0. \qquad (3)$$

Here pressure anisotropy of the plasma species is represented by $A_j = (\beta_{\parallel j} - \beta_{\perp j})$, where $\beta_{\parallel j}$ and $\beta_{\perp j}$ are respectively the parallel and the perpendicular plasma beta for the jth species, and $V_{Ap} = B_0/(4\pi\rho_p)^{1/2}$ is the Alfvén speed with respect to the proton mass density $\rho_p = N_p m_p$.

Neglecting the oxygen ion dynamics in (3), and considering $\omega^2 \ll \frac{N_o m_e}{N_p m_p}\Omega_e\omega$, we get the helicon mode in multi-ion plasma

$$\omega_0 = \pm\frac{N_e}{N_o}\left(1 - \frac{A_e}{2} - \frac{A_p}{2}\right)\frac{k^2c^2}{\omega_{pe}^2}\Omega_e, \qquad (4)$$

This is very similar in structure to the dispersion relation for the usual helicon mode,

$$\omega_H = \frac{k^2c^2}{\omega_{pe}^2}\Omega_e, \qquad (5)$$

in electron -proton plasma. Equation (4) shows that electron dynamics dominates the interaction between the electromagnetic waves and the multi-ion plasma. *Now, we shall take into account the dynamics of the* O^+ ions, and look for an instability near the helicon mode frequency ω_0. Considering $\omega^2 \ll \frac{N_o}{N_p}\Omega_p\omega$, and writing $\omega = \omega_0 + \delta$, (3) simplifies to

$$\delta^3 + [2(\omega_0 - kU_o) \pm \Omega_o]\delta^2 + (\omega_0 - kU_o)^2\delta \mp \left[-\frac{A_o k^2 V_{Ap}^2}{2R} + (\omega_0 - kU_o)(\omega_0 - kU_o \pm \Omega_o)\right]\Omega_o = 0, \quad (6)$$

where $R = (N_o m_o / N_p m_p)$ represents the relative oxygen ion mass density with respect to protons.

We solved (6) using *Mathematica* for both RH and LH polarized modes. We find that the helicon mode instability occurred for the RH mode only. Therefore results for the real frequency, $\omega_r = (\omega_0 + Re\,\delta)$ and growth rate, $\gamma = Im\,\delta > 0$ for RH modes are shown in Figures 1–2 for the parameters relevant to the central plasmasheet (CPS) region where we have taken $\beta_{\parallel o} = 3.5$ [*Daglis et al.*, 1991; *Lennartsson*, 1994].

Ranges of real frequencies and growth rate increase when A_o is increased (Figures 1a and 1b), and growth rates peak for a certain value of the normalized wavenumber. In Figures 2a and 2b (and in Figures 3 and 4), we have to truncate the curves for real frequency and the growth rates before the latter could attain the maximum value, say γ_{max}/Ω_o. The truncation was necessary as the assumption of treating the oxygen ions as cold, i.e.,

$$\eta_0^2 = \frac{R\Omega_o^2}{\beta_{\parallel o} k^2 V_{Ap}^2}\left|\frac{\omega}{\Omega_o} - \frac{MkV_{Ap}}{\Omega_o} + 1\right|^2 \gg 1, \quad (7)$$

breaks down for values of the wavenumber kV_{Ap}/Ω_o larger than those shown in Figures 2a and 2b.

An increase of $M = U_o/V_{Ap}$, the oxygen ion Alfvén Mach number with respect to the proton Alfvén speed, and R has destabilizing effects on the helicon mode (Figures 2a and 2b). Positive (negative) values of proton anisotropy, A_p, lead to increased (decreased) values for real frequencies as well as growth rates (not shown). The effects due to electron ansiotropy, A_e, were found to be insignificant (not shown).

2.2 Neutralized O^+ ion beam

We consider an ionospheric O^+ ion beam passing through the plasmasheet region where the current carried by O^+ ions is neutralized by the equilibrium electron drift velocity satisfying the condition, $U_e = N_o U_o / N_e$ (once again $U_p = 0$). Such a situation corresponds to no net field-aligned current in the system in the equilibrium state. Then, once again considering low frequencies (compared to ion plasma frequencies),

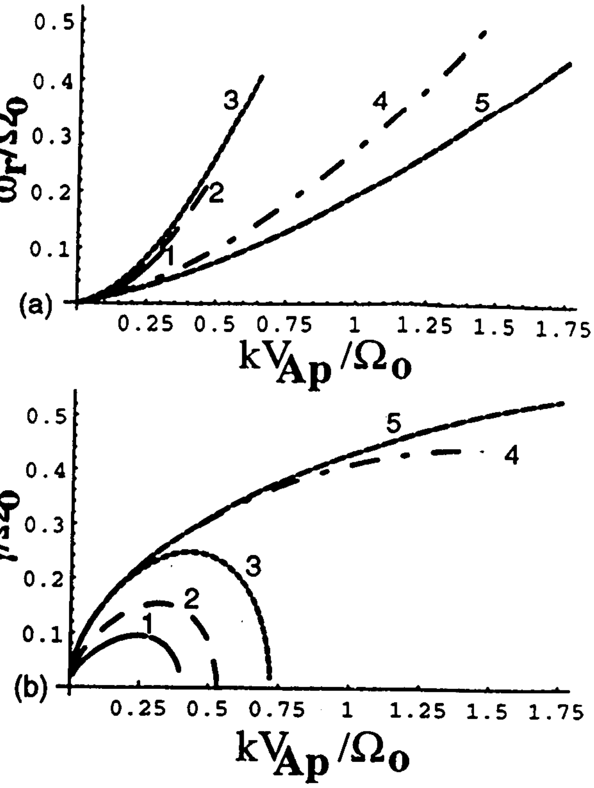

Figure 2. Variation of normalized real frequency ω_r/Ω_o (a), and growth rate γ/Ω_o (b) versus normalized wavenumber kV_{Ap}/Ω_o for the helicon mode instability driven by O^+ ions in the CPS region for $A_e = A_p$=0, and A_o = 2.0. For the curves 1, 2, and 3, M=0.05, and R= 1.0, 5.0, and 10.0 respectively. For the curves 4 and 5, R= 10.0 and M= 0.1, and 0.2 respectively.

(2) can be simplifies to

$$\omega^2 \pm \frac{N_o}{N_p}\frac{(\omega - kU_o)^2\Omega_p}{(\omega - kU_o \pm \Omega_o)} - k^2V_{Ap}^2\left(1 - \frac{A_e}{2} - \frac{A_p}{2}\right) + \frac{A_o k^2 V_{Ap}^2 \Omega_o^2}{2(\omega - kU_o \pm \Omega_o)^2} = 0. \quad (8)$$

As mentioned above, to get the helicon modes, it is important to break the MHD constraint of $\omega << \Omega_o$ for the oxygen ions. For example, for $(\omega - kU_o) >> \Omega_o$ (unmagnetized oxygen ions), taking A_o=0, and neglecting the first term compared to the second term, (8) gives:

$$\omega - kU_o = \pm\frac{N_e}{N_o}\left(1 - \frac{A_e}{2} - \frac{A_p}{2}\right)\frac{k^2c^2}{\omega_{pe}^2}\Omega_e \quad (9)$$

which is very similar to (3) except for the Doppler shifted term on the left-hand side. Equation (8) indeed predicts right-hand mode instability for the case of unmagnetized oxygen ions (i.e., $(\omega - kU_o) >> \Omega_o$). For simplicity, let us take $A_e = A_p = U_o = 0$ and neglect the first term compared to the second term in (8). Considering the minus sign in (8), we get

$$-\omega - \omega_0 + \frac{A_o \omega_0 \Omega_o^2}{2\omega^2} = 0, \tag{10}$$

where $\omega_0 = (k^2 V_{Ap}^2 / R\Omega_o)$. On writing $\omega = -\omega_0 + \eta$, with $\eta \ll \omega_0$, the above equation yields an approximate solution,

$$\omega_r = -\frac{3}{4}\omega_0,$$
$$\gamma = Im\ \eta = \Omega_o \left(A_o - \frac{\omega_0^2}{4\Omega_o^2} \right)^{1/2}. \tag{11}$$

The mode is unstable provided $A_o > \frac{\omega_0^2}{4\Omega_o^2}$.

Now the polarization, P, for the case of parallel propagating electromagnetic modes can be written as [*Winske and Gary*, 1986]:

$$P \equiv \pm \frac{\omega_r}{|\omega_r|}, \tag{12}$$

where the plus or minus sign refers to the corresponding signs in (8), and $P = +1$ (-1) corresponds to right-hand (left-hand) polarization. From (10) above it is clear that the unstable helicon mode would have a right-hand polarization. If one was to start with the positive sign in (8) and redo the analysis, one would arrive at the above solution but with $\omega_r = +\frac{3}{4}\omega_0 > 0$. This again leads to the unstable helicon modes being right-handed polarized. The unstable modes, because of our assumption of unmagnetized O^+ ions, would occur much above the oxygen cyclotron frequency.

We have numerically solved (8) for both RH and LH polarized modes, and for the case of weakly magnetized oxygen ion beams. For the parameters considered in Figures 3 and 4, both RH and LH modes were found to be unstable. The growth rate of the LH modes were usually smaller than the RH modes. Since the helicon modes have RH polarizations, we have shown the results for the RH modes only. In general, the instability occurs for larger values of A_o, M, and R as compared to the case of non-neutral O^+ ion beam. The growth rates as well as the real frequencies are increased by the increases in A_o and A_p (cf. Figures 3a and 3b), M (Figures 4). The range of unstable wavenumber is increased by an increase in R. Note that many curves in Figures 3 and 4 are truncated to satisfy the inequality (7).

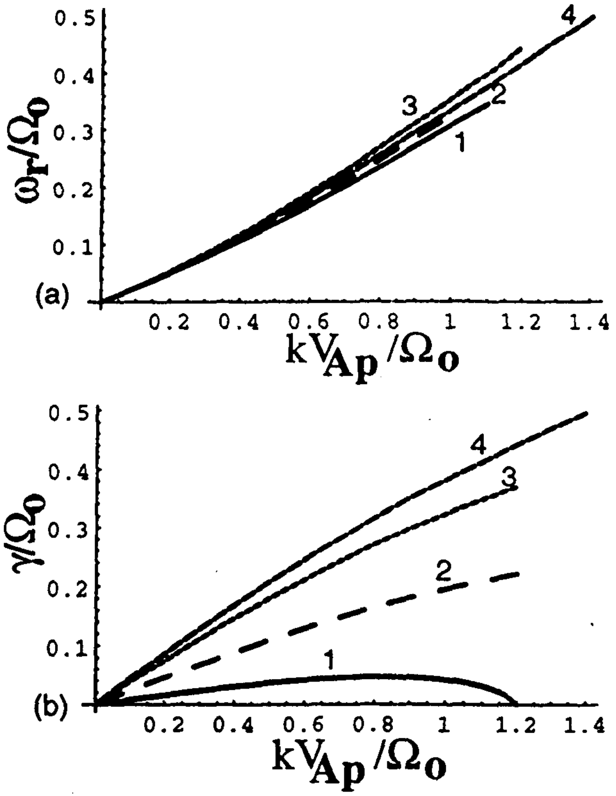

Figure 3. Variation of normalized real frequency ω_r/Ω_o (a), and growth rate γ/Ω_o (b) versus normalized wavenumber kV_{Ap}/Ω_o for the RH mode (helicon) instability driven by O^+ ions in the CPS region for A_e=0, M = 0.25, and R = 10.0. For the curves 1, 2, and 3, A_p = 0.0, and A_o = 2.0, 3, and 5, respectively. For curve 4, A_o =5 and A_p = 1.0. Note that LH mode is also excited for parameters considered here as well as in Figure 4. However, the growth rates of the LH modes are smaller than the RH modes and hence not shown.

3. Discussion and Application to Substorms

Our analysis shows that the presence of ionospheric O^+ ions in the central plasmasheet (CPS) can excite helicon mode instability during the growth phase of substorms. For the case of a neutralized O^+ ion beam, when both the charge and the current neutrality conditions are satisfied in the equilibrium state, modes with both RH and LH polarizations could become unstable for the case of weakly magnetized O^+ ion beams. The helicon modes, however, lie on the RH branch. On the other hand, for the case of a nonneutral ionospheric O^+ ion beam passing through the plasmasheet region (corresponding to a finite field-aligned current in the equilibrium state), only the helicon modes with RH polarization are found to be excited below (or comparable to) the oxygen ion cyclotron frequencies for the parameters relevant to the plasmasheet region. We find that the parallel Mach number, M, of the oxygen ions gives rise to the larger effective $\beta_{\parallel o}$ thus, leading to destabilization of the mode below the classical fire-hose instability limit. The helicon mode is quite distinct from the right hand resonant beam instability [*Gary et al.*, 1985; *Tsurutani et al.*, 1985]. Helicon mode instability is excited at much lower (than the proton cyclotron) frequencies, at much longer wavelengths, and at smaller Mach numbers than the right hand beam resonant in-

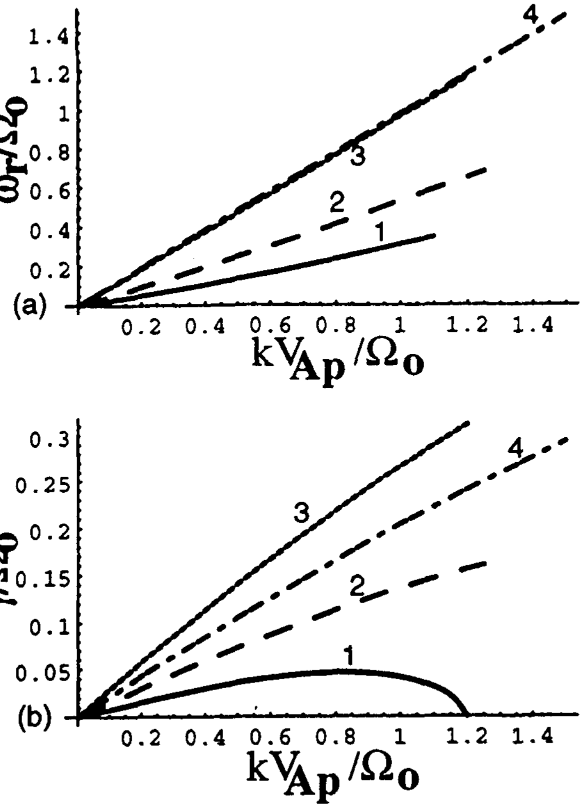

Figure 4. Variation of normalized real frequency ω_r/Ω_o (a), and growth rate γ/Ω_o (b) versus normalized wavenumber kV_{Ap}/Ω_o for the RH mode instability driven by O^+ ions in the CPS region for $A_e = A_p = 0$, and $A_o = 2.0$. For the curves 1, 2, and 3, = 0.0, $R = 10.0$ and $M = 0.25$, 0.5, and 1.0, respectively. For curve 4, $M = 1.0$ and $R = 20.0$.

stability (typically $M \geq 1$). Based on observations and theoretical models, we consider the following parameters for the the central plasmasheet in the region $X \sim$ -10 R_E to -15 R_E: A_0 =0.1 to 2.0 [*Daglis et al.*, 1991; *Lennartsson*, 1994; *Cladis and Francis*, 1992], $R = 1 -$ 10 [*Wilken et al.*, 1995], and $|U_o - U_p| \approx 10 - 60$ km s^{-1} [*Peterson et al.*, 1981; *Orsini et al.*, 1985]. Then, for $B_0 = 10$ nT and $N_p = 0.5$ cm^{-3}, we get typical Mach numbers $M = 0.025 - 0.25$ in the CPS region.

Figures 1 –4 show that the range of excited real frequencies, growth rates, and unstable wavelengths, $\lambda = 2\pi/k$, are respectively $\omega_r = (0.1 - 1.5)\ \Omega_o = (1.0 - 15.0)$ mHz, $\gamma = (0.1\text{–}0.5)\ \Omega_o = (1.0 - 5.0)$ mHz, and $\lambda = V_{Ap}/(0.1 - 1.75)\Omega_o = (1 - 15)\ R_E$ for $M = (0.01 - 0.25)$, $R = 1 - 10$, $A_o = 0.1 - 2.0$, $B_0 = 10$ nT and $N_p = 0.5$ cm^{-3}. Hence the instability would preferentially excite low-frequency waves with wavelenghts $\sim$ (0.8 – 15) R_E in the CPS. The typical e-folding time of the instability is about 3 to 15 minutes at wavelengths of $\lambda \approx 1$ to 5 R_E, which is reasonably short. Therefore, these modes could attain saturation as the enhanced convection events may last for a few hours.

The existence of large amplitude helicon modes driven by the free energy of the ionospheric-origin O^+ ion beams in the CPS region may CPS have some interesting consequences for the substorm processes. The large scale fluctuating z and y components, i.e., δB_z and δB_y, associated with the helicon modes could twist the equilibrium magnetic field into flux ropes. This gives an indication that the helicon modes may be playing some role in the processes related to oxygen ion bursts associated with multiple flux ropes in the distant magnetotail as observed by GEOTAIL [*Wilken et al.*, 1995]. The large amplitude δB_z could produce localised minima in the z component of the 2D equilibrium magnetotail magnetic field near the neutral axis. Moreover, the low-frequency turbulence due to the helicon modes could scatter electrons trapped in the CPS region. Both these factors would make these localized minima (separated by the wavelength of the excited modes) to be the potential site for the excitation of the tearing mode instabilities which could lead to the onset of the expansion phase of the substorm. Further, the helicon mode may be responsible for some of the low-frequency RH polarized electromagnetic noise in the ULF - ELF frequency range observed in the CPS and plasmasheet boundary layer [*Russell*, 1992; *Tsurutani et al.*, 1985, 1987; *Bauer et al.*, 1995].

Oxygen ions at times are found to dominate the energy density of the storm-time ring current [*Hamilton et al.*, 1988]. The origin of these oxygen ions is one of the major puzzle for magnetic storm research [*Tsurutani et al.*, 1997]. It has recently been noted that dayside boundary layer/cusp O^+ and H^+ ions are heated/accelerated essentially all of the time by the intense broadband plasma waves. During southward interplanetary magnetic field events, these ions could be convected in the anti-sunward direction across the polar cap and into the plasmasheet [*Tsurutani et al.*, 1998]. We speculate that if the oxygen ions form anisotropic beams in the inner plasmasheet as discussed here, they provide an ideal situation for the excitation of the helicon mode instability and substorm onset. Consequential injection of this plasma inward into the Earth's nightside magnetosphere by the storm electric fields could then lead to enhanced oxygen ions in the storm-time ring current .

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